STUDIES ON CONVECTION IN POLAR OCEANS

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LONG TERM GOALS

The long term goals of our research program are to identify fundamental hydrodynamical processes related to polar oceanography and to study them in-depth using laboratory, theoretical and numerical modeling.

OBJECTIVES

The objectives of our current research are to study processes related to the violent mixing phase of deep ocean (or chimney) convection. In particular, the emphasis is on the following aspects: (i) how various sources of turbulence (e.g., mechanical turbulence due to wind stirring and buoyancy induced turbulence due to surface cooling) interact to produce a deep convective layer; (ii) the role of each turbulent source at various depths of convection; and (iii) the mechanisms of lateral buoyancy transport from the convective region.

APPROACH

Laboratory modeling and accompanying theoretical analyses are the key approaches used to achieve the above objectives. The experimental apparatus consisted of a cylindrical tank containing either density stratified or homogeneous water, with a (negative) buoyancy source of finite diameter located at the center of the water surface. The entire tank assembly was placed on a rotating table to simulate Coriolis forces due to Earth's rotation. The buoyancy source was a dense salt-water shower, carefully designed to deliver a steady buoyancy flux uniformly distributed over the source. Located under the source was a wire-mesh grid, oscillations of which produced mechanical turbulence that decayed as a function of the distance from the grid. The turbulent convection produced under the buoyancy source could be modified by activating the grid, and the combined effects of two turbulent sources could be investigated by measuring the propagation speed of turbulent front (using laser-induced fluorescence technique) and the turbulent velocity and lengthscales (using digital particle-tracking velocimetry). The turbulence introduced by the two sources was studied separately and in combination, so that the conditions for the dominance of each source could be delineated.

The depth of convection subject to rotation and stratification and the lateral evolution of the convecting region was also studied. The observations included the vertical scale of convection, time for the onset of baroclinic instabilities at the lateral front, the lateral buoyancy transport mechanisms and the decay of turbulence upon switching off of the buoyancy source. Digital image processing techniques based on video recordings made from several views were employed to capture various aspects of flow evolution.

ACCOMPLISHMENTS

Research on all of the above issues has been initiated, some are completed and the others are in progress. The completed work includes: (i) the development of a criterion to elucidate relative contributions of wind (mechanical) and convective (buoyancy-driven) turbulence, when both sources are contributing; (ii) the establishment of the depth of the convecting layer in the presence of rotation and stratification (or the depth of the chimney, in the case of oceans); and (iii) the demonstration of possible existence of "hetons" around chimneys, which contribute immensely to the lateral buoyancy transport out of the chimney.

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SCIENTIFIC/TECHNICAL RESULTS

Studies on turbulent convection in the presence of mechanically generated turbulence clearly show how the latter, say induced by the wind stirring of ocean surface, strongly modifies the convective turbulence. The measurements of the turbulent front propagation reveal that the depth of the turbulent layer h at a time t is given by h ~ (Bt)**3/2, when the turbulent layer is driven by a buoyancy flux B, and h ~ (Kt)**1/2, when the turbulence is produced by a mechanical stirring source that produces turbulence specified by an eddy viscosity K. When both turbulence sources are present, however, the dominating source is determined by the turbulent intensities that would have been present when one or the other source is not present . Figure 1 shows a plot of normalized turbulent layer height H = h/[(Bt**3)**1/2] versus the non-dimensional time parameter T = B(t**2)/K, which clearly demonstrates how at small t or B (T << 0.5) the turbulent-layer propagation is controlled by the mechanical source (h ~ t**1/2) and that buoyancy-dominated turbulence exists at large T. Detailed calculations indicate that both mechanical and buoyancy-induced turbulence are important when 0.3 < U/W < 0.9, where W = (Bh)**1/3 is the convection velocity and U is the characteristic velocity of mechanical turbulence.

Research on the vertical growth and lateral evolution of convecting layer (conducted in the absence of mechanical stirring) explicated a number of interesting aspects. It was found that, in the presence of stratification, the depth of the convecting layer is governed by a balance between vertical inertia and buoyancy forces of turbulent eddies, irrespective of background rotation. This vertical scale determines the properties of the rim currents and ensuing baroclinic eddies that shed out of the convecting patch. Initial experiments performed without stratification, but with the convecting region bounded by a solid bottom, clearly indicated that buoyancy transport from the chimney into ambient fluid occurs by "hetons." These hetons are characterized by a stratified fluid column, having a cyclonic circulation at the top, an anticyclonic circulation at depth and domed isopycnals within. Figure 2 shows the side-view photograph of a heton shedding out of the central convecting chimney as the time progresses. Here the convecting fluid is dyed, and hence its lateral transport out of the convecting region is marked by domed-shaped dyed fluid. Detailed velocity observations indicate that the flow indeed changes from cyclonic to anticyclonic along the depth of the shed fluid elements from the convective region.

IMPACT FOR SCIENCE AND SYSTEMS APPLICATIONS

The results of the multiple turbulent source study delineate a criterion that identifies the regimes of oceanic chimney convection controlled by wind stirring or the unstable buoyancy flux. For oceans, this criterion can be expressed in terms of the Monin-Obukhov lengthscale; i.e. at depths h > 0.75(U**3)/B, wind stirring is unimportant. For typical values of B ~ 10-7 m**3/s and U = 5 cm/s, this critical depth becomes ~1 km. The other fundamental results on the maximum depth of the chimney, rim-current velocity, time scales for baroclinic instability and flux transport by hetons can readily be used to interpret field observations and to develop sub-grid parameterizations for Oceanic General Circulation Models.

TRANSITIONS

The results based on controlled laboratory experiments will be of immense utility in interpreting field observations taken during the ONR-sponsored deep convection experiments in the Labrador Sea. To this end, we will maintain close contacts with the researchers involved in the field experiment. Also, fundamental results obtained in our previous convection work have been incorporated into several numerical models and/or have been used to check the accuracy of numerical schemes (e.g. Lavelle & Smith 1996, Journal of Physical Oceanography, 26, 863-872).

RELATED PROJECTS

The P.I. is involved in a National Science Foundation (NSF) funded multidisciplinary project entitled "Modeling of Contaminant Dispersion in Complex Terrain Flows," dealing with convection and aerosol distribution in the US desert Southwest (with particular applications to air pollution dispersion in Phoenix area). The project being reported herein differs from the NSF project in that the buoyancy source is localized and the Rossby radius of deformation is small enough for the lateral transport to be governed by baroclinic instabilities.

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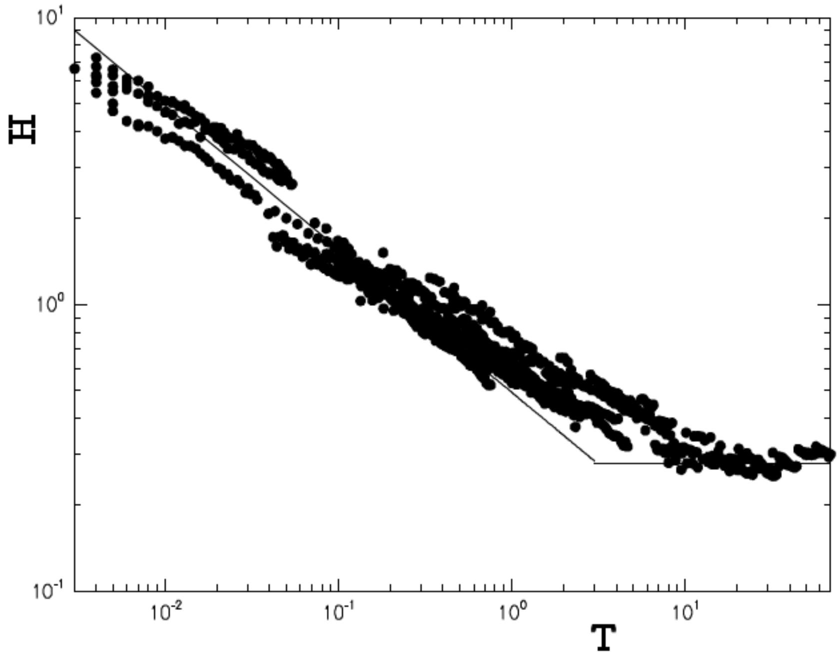

Figure 1: A graph of the non-dimensional convective-layer depth H as a function of non-dimensional time parameter T. Mechanical turbulence dominates at small T whereas convection becomes important at large T.

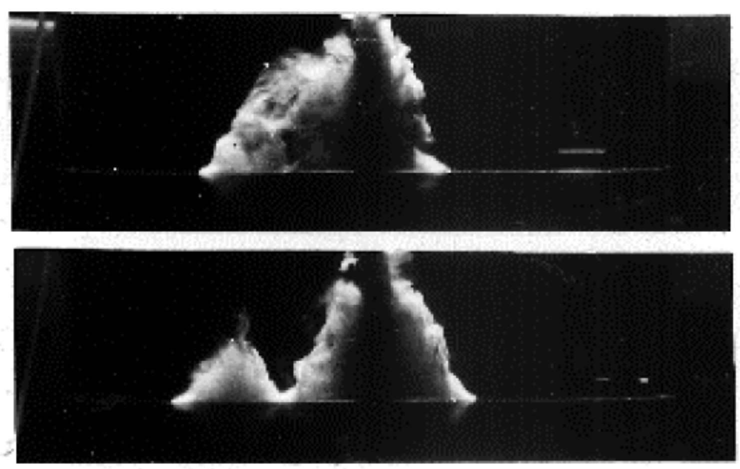

Figure 2: The evolution of a shallow convecting region in the presence of background rotation. Here the dense water (colored) is introduced from a disk-shaped source and is allowed to descend to a limited depth, as in the case of deep ocean convection. Detailed measurements show that the lateral transport of buoyant fluid from the main convecting chimney occurs by "hetons" having a cyclonic circulation at the top, an anticyclonic circulation at the bottom and domed isopycnals. The ejection of a heton is clearly visible during the evolution of the main plume.